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Municipal Waste Combustion Assessment: Fossil Fuel Co-Firing

Energy and Environmental Research Corp., Durham, NC

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MUNICIPAL WASTE COMBUSTION ASSESSMENT: FOSSIL FUEL CO-FIRING

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16. ABSTRACT The report identifies refuse derived fuel (RDF) processing operations and various RDF types; describes such fossil fuel co-firing techniques as coal fired spreader stokers, pulverized coal wall fired boilers, pulverized coal tangentially fired boilers, and cyclone fired boilers; and describes the population of coal fired boilers that currently co-fire RDF, have previously co-fired RDF but have ceased to do so, and have been used in RDF co-firing demonstrations. (Fossil fuel co-firing, defined as the combustion of RDF with another fuel (usually coal) in a device designed primarily to burn the other fuel, is generally confined to commercial and utility boilers.) Model plants are developed and good combustion practices are recommended.

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ABSTRACT

Fossil fuel co-firing is defined as the combustion of RDF with another fuel (usually coal) in a device designed primarily to burn the other fuel. Fossil fuel co-firing is generally confined to commercial and utility boilers. This report identifies RDF processing operations and various RDF types; describes fossil fuel co-firing technologies including coal fired spreader stokers, pulverized coal wall fired boilers, pulverized coal tangentially fired boilers and cyclone fired boilers; describes the population of coal fired boilers that currently co-fire RDF, have previously co-fired RDF but have ceased to do so, and units that have been used in RDF co-firing demonstration projects. Model plants are developed and good combustion practices are recommended.

FOREWORD

Based upon its analysis of Municipal Waste Combustors (MWC), the Environmental Protection Agency (EPA) has determined that MWC emissions may reasonably be anticipated to contribute to the endangerment of public health and welfare and warrant further legislation. As a result, EPA's Office of Air Quality Planning and Standards is developing emission standards for new MWCs under Section 111(b) of the Clean Air Act (CAA) and guidelines for existing MWCs under Section 111(d) of the CAA.

In support of these regulatory development efforts, the Air and Energy Engineeering Research Laboratory in EPA's Office of Research and Development has conducted an in-depth assessment of combustion control practices to minimize air emissions from MWCs. The results of this assessment are documented in the following reports:

Municipal Waste Combustion Assessment: Combustion Control at New Facilities, August 1989 (EPA-600/8-89-057)

Municipal Waste Combustion Assessment: Combustion Control at Existing Facilities, August 1989 (EPA-600/8-89-058)

Municipal Waste Combustion Assessment: Fossil Fuel Co-Firing, July 1989 (EPA-600/8-89-059)

Municipal Waste Combustion Assessment: Waste Co-Firing, July 1989 (EPA-600/8-89-060)

Municipal Waste Combustion Assessment: Fluidized Bed Combustion, July 1989 (EPA-600/8-89-061)

Municipal Waste Combustion Assessment: Medical Waste Combustion Practices at Municipal Waste Combustion Facilities, July 1989 (EPA-600/8-89-062)

Municipal Waste Combustion Assessment: Technical Basis for Good Combustion Practice, August 1989 (EPA-600/8-89-063)

Municipal Waste Combustion: Multi-pollutant Study, Emission Test Report, Maine Energy Recovery Company, Refuse-Derived Fuel Facility, Biddeford, Maine, Volume I, Summary of Results, July 1989 (EPA-600/8-89-064a)

Municipal Waste Combustion: Multi-Pollutant Study, Emission Test Report, Mass Burn Refractory Incinerator, Montgomery County South Ohio, Volume I, Summary of Results, August 1989 (EPA-600/8-89-065a)

The specific objectives of this report, "Municipal Waste Combustion Assessment: Fossil Fuel Co-Firing," were to provide an overview of fossil fuel co-firing technology and identify the extent to which fossil fuel co-firing is practiced. Fossil fuel co-firing is defined as the combustion of RDF with another fuel (usually coal) in a device designed primarily to burn the other fuel. Fossil fuel co-firing is generally confined to commercial and utility boilers.

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1.0 FOSSIL FUEL CO-FIRING TECHNOLOGY

This section defines fossil fuel co-firing, identifies refuse derived fuel (RDF) processing operations and various RDF types, and describes fossil fuel co-firing technologies.

1.1 Definition

Fossil fuel co-firing is defined as the combustion of RDF with another fuel (usually coal) in a device designed primarily to burn the other fuel. Fossil fuel co-firing is generally confined to commercial and utility boilers.

1.2 Description of Technology

1.2.1 RDF Processing

Process steps or unit operations used to produce RDF may include: receiving, picking, handling and conveying, size reduction, classification, densification, and storage. The degree and order in which these steps are utilized is highly site-specific, resulting in different RDF characteristics from different RDF processing plants. Depending on the degree of processing, RDF can range from coarse-shredded material to a powdered form. The various types of RDF have been classified by the American Society for Testing and Materials (ASTM) and are listed in Table 1-1.[1] A typical moisture content for coarse RDF (c-RDF) and fluff RDF (f-RDF) is 25 percent whereas powdered RDF (p-RDF) typically contains less than 5 percent moisture. Correspondingly, typical heating values for coarse and fluff RDF are 4500-6000 Btu/lb (1.05-1.40 x 10^7 J/kg) whereas powdered RDF approaches 7500 Btu/lb (1.74 x 10^7 J/kg). A typical process for producing c-RDF for use in a spreader stoker boiler is illustrated in Figure 1-1.[1] Unit operations used in this process include coarse shredding; ferrous and aluminum separation, screening to remove glass, grit and dirt; fine shredding, and air classification to remove the heavy fraction.

1.2.2 Description of Combustion Technology

All of the currently operating facilities which meet the definition of fossil fuel co-firing are coal fired boilers. RDF has been co-fired in all four of the common types of coal fired boilers (spreader stoker, wall fired

TABLE 1-1. ASTM CLASSIFICATION OF REFUSE DERIVED FUELS

TYPE OF RDF	DESCRIPTION
RDF-1 (MSW)	Municipal solid waste used as a fuel in as-discarded form, without oversize bulky waste (OBW).
RDF-2 (c-RDF)	MSW processed to coarse particle size, with or without ferrous metal separation, such that 95 weight percent passes through a 6 inch square mesh screen.
RDF-3 (f-RDF)	Shredded fuel derived from MSW and processed for the removal of metal, glass, and other entrained organics. The particle size of this material is such that 95 weight percent passes through a 2 inch (5.1 cm) square mesh screen. Also called "fluff RDF."
RDF-4 (p-RDF)	Combustible waste fraction processed into powdered form, 95 weight percent passing through a 10-mesh (0.035 inch or 0.89 cm square) screen.
RDF-5 (d-RDF)	Combustible waste fraction densified (compressed) into the form of pellets, slugs, cubettes, briquettes, or some similar form.
RDF-6	Combustible waste fraction processed into a liquid fuel (no standards developed).
RDF-7	Combustible waste fraction processed into a gaseous fuel (no standards developed).

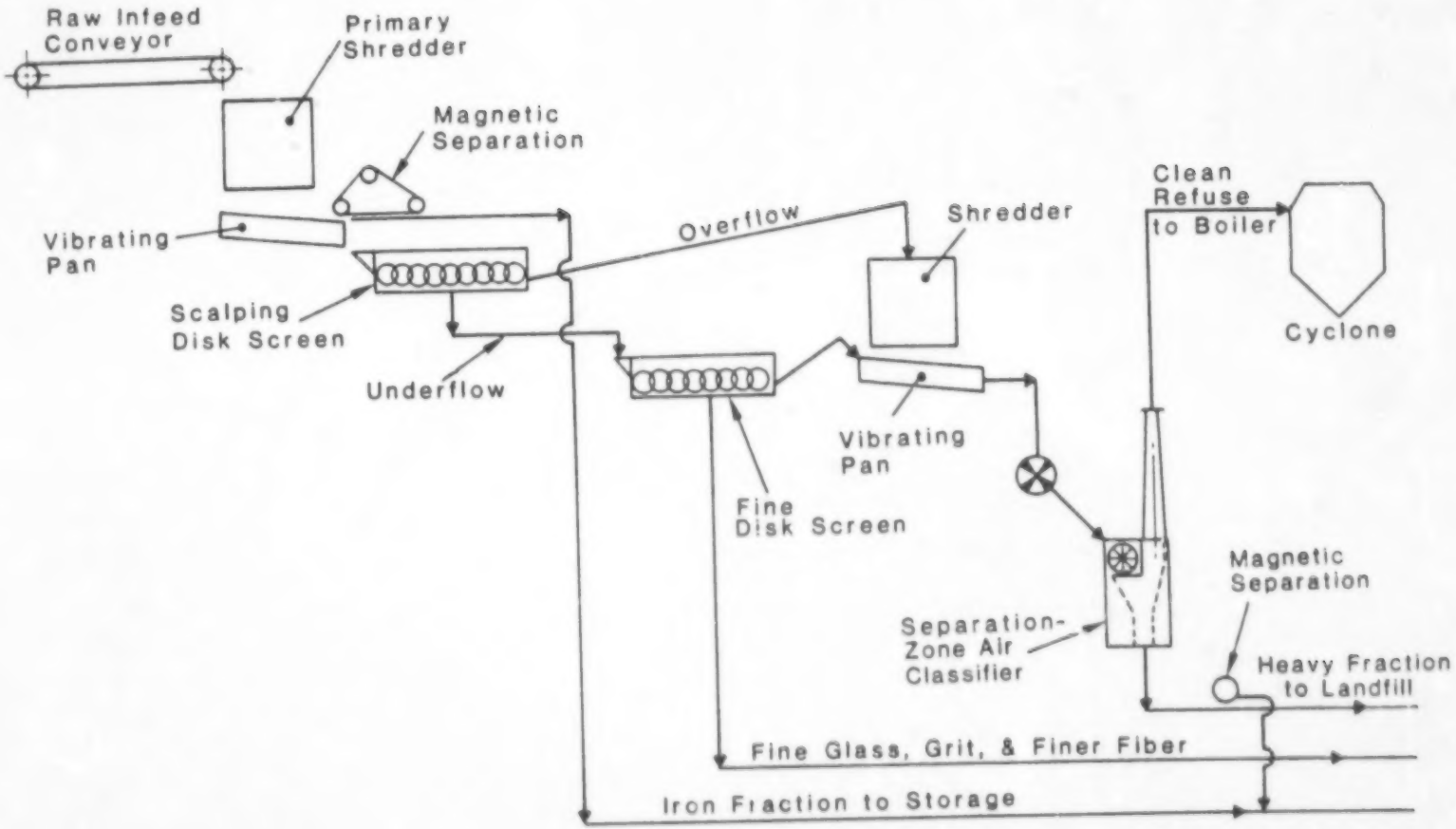

Figure 1-1. Schematic of Typical RDF Processing

pulverized coal, tangentially fired pulverized coal, and cyclone). However, there are no spreader stokers known to be co-firing RDF at this time.

1.2.2.1 Coal Fired Spreader Stokers

A diagram of a typical coal fired spreader stoker is shown in Figure 1-2.[1] In general, spreader stokers can use a wide variety of coals though they work best if the feed used at any one time is fairly uniform. The coal typically ranges in size from 1/2 inch (0.013 m) down to 100 μm. As the name implies, the spreader stoker projects fuel into the furnace over the traveling grate with a uniform spreading action which permits suspension burning of the fine fuel particles. The larger particles which can not be supported by the gas flow fall to the grate where they form a thin fast-burning bed. Peak temperatures in a spreader stoker occur above the bed in a region where volatile material evolving from the coal on the bed is burning in conjunction with suspension burning of the smaller coal particles. Approximately half of the coal burns in suspension and half burns on the grate. The traveling grate moves from the back of the furnace to the front where the ash is discharged into an ash hopper.

Spreader stokers are well suited to co-fire RDF. The units provide fuel residence times from several minutes to more than an hour depending on grate speed and the location at which the RDF lands on the grate. Long fuel residence times allow the large RDF particles sufficient time to burn out. RDF variability is a potential problem. Changes in RDF particle size and density make even distribution of the RDF on the grate difficult. Poor distribution of the waste can lead to fuel rich areas which can produce higher organic emissions. It is also possible for large particles with relatively low densities to be entrained and carried out of the combustion chamber before the hydrocarbons are completely oxidized. If densified RDF rather than coarse or fluff RDF is used, problems associated with non-uniform waste feed and combustion can be substantially alleviated.

1.2.2.2 Pulverized Coal Wall Fired Boiler

A typical wall fired pulverized coal boiler that has been modified to fire RDF is shown in Figure 1-3.[2] The coal is pulverized to create a powder in which 70 weight percent of the coal particles are smaller than

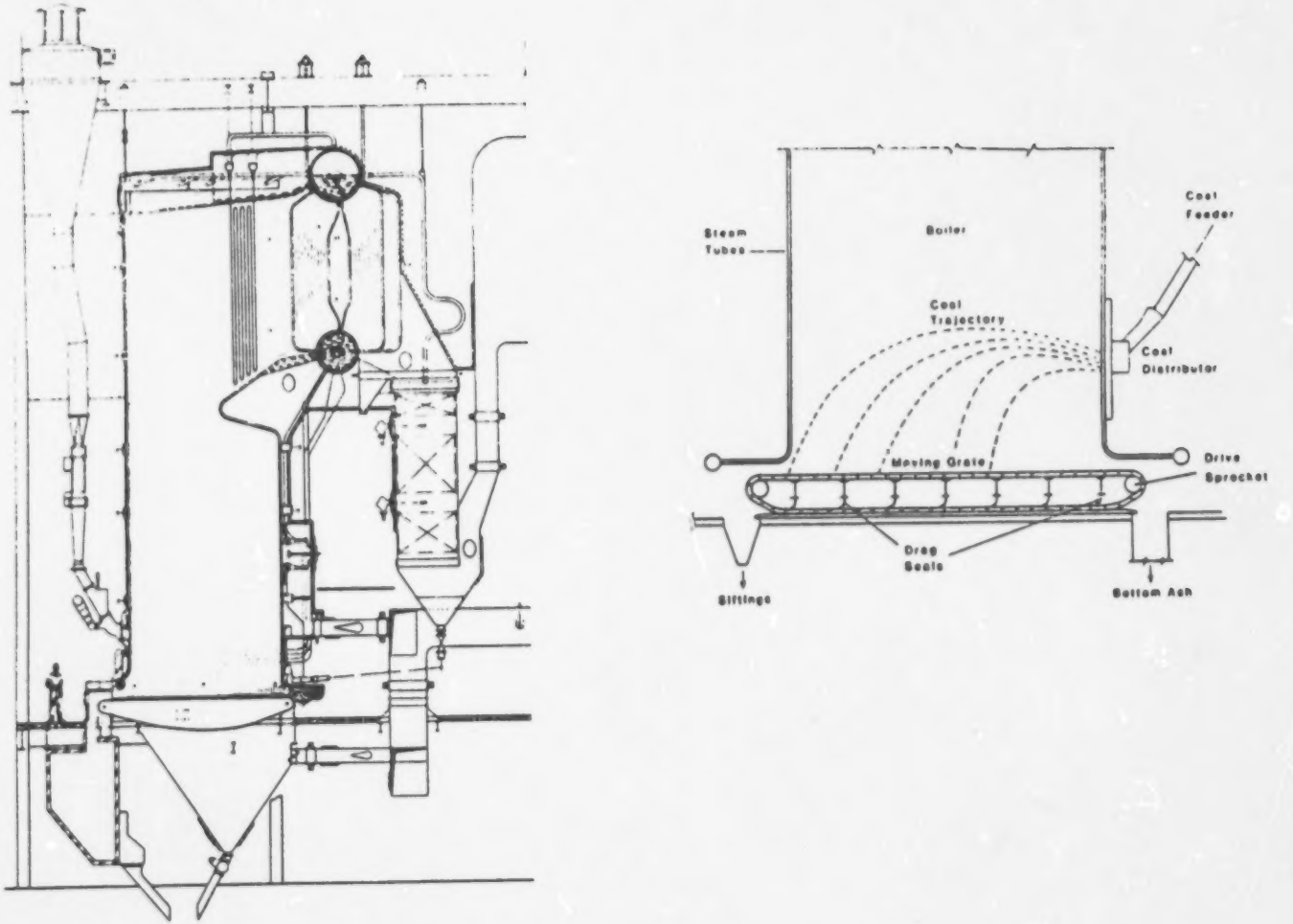

Figure 1-2. Profile of a Typical Coal Fired Spreader Stoker Boiler

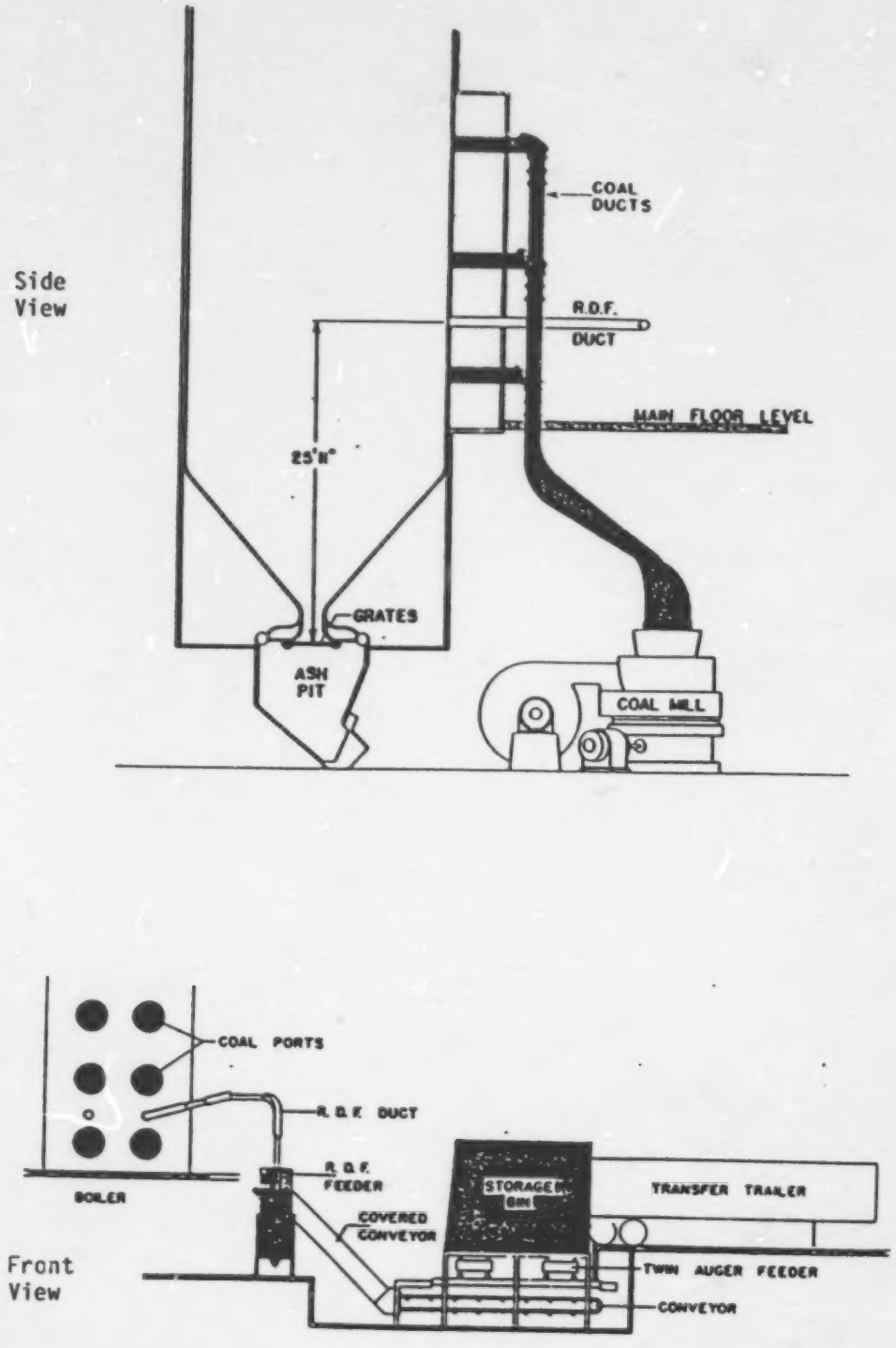

Figure 1-3. Wall Fired Pulverized Coal Boiler Modified to Co-Fire RDF

approximately 75 μm. This powder is then injected into the boiler through wall fired burners. The coal ignites and burns rapidly in suspension. Typically over 80 percent of the ash produced is entrained and carried into the convective sections of the boiler.

To implement RDF co-firing capability, separate air transport injectors are installed. The injectors are essentially ducts through which RDF is forced by blowing air (similar to distributors in spreader stokers). The RDF used typically has a nominal size of 2 inches (0.05 m) and requires relatively long burnout times. A significant fraction of these large particles disengage from the gas flow; therefore, drop grates are added to the boilers to ensure complete burnout of the RDF that falls to the furnace bottom. Drop grates are stationary grates installed in the lower furnace to catch partially burned RDF. Ash is allowed to accumulate on the grate. After the layer of ash on the grates reaches a predetermined height, the grate slats are tipped sideways and the ash falls into the ash hopper. These grates change the heat transfer characteristics of the furnace by shielding the ash hopper from radiative heat transfer. Radiative heat transfer creates high grate temperatures which may lead to slagging and clinker formation. It may be necessary to address this potential problem when the grates are designed and installed by adjusting the distribution of underfire and overfire air.

1.2.2.3 Pulverized Coal Tangentially Fired Boiler

In a tangentially fired boiler, each corner of the furnace contains a vertical arrangement of burners. Pulverized coal entrained in 15-20 percent of the total combustion air (primary air) is injected through coal nozzles which are placed between secondary air nozzles, as illustrated in Figure 1-4.[3] Both the coal and the combustion air are directed along the tangent lines of a small circle in the center of the furnace. This results in the formation of a large vortex. Combustion occurs in suspension and there are no grates. The nozzles can be tilted up, set horizontally, or tilted down in order to control exit gas temperature. During normal operation, ash builds up and insulates the furnace walls, decreasing the amount of heat absorbed by the furnace, thus causing exit gas temperatures to increase. To compensate, the nozzles are automatically tilted down to expose the gases to the maximum amount of wall surface area. This maximizes furnace heat absorption and maintains exit gas temperatures. After sootblowing occurs, the cleaner wall surfaces absorb more heat which decreases the exit gas temperature. In this case, the nozzles are

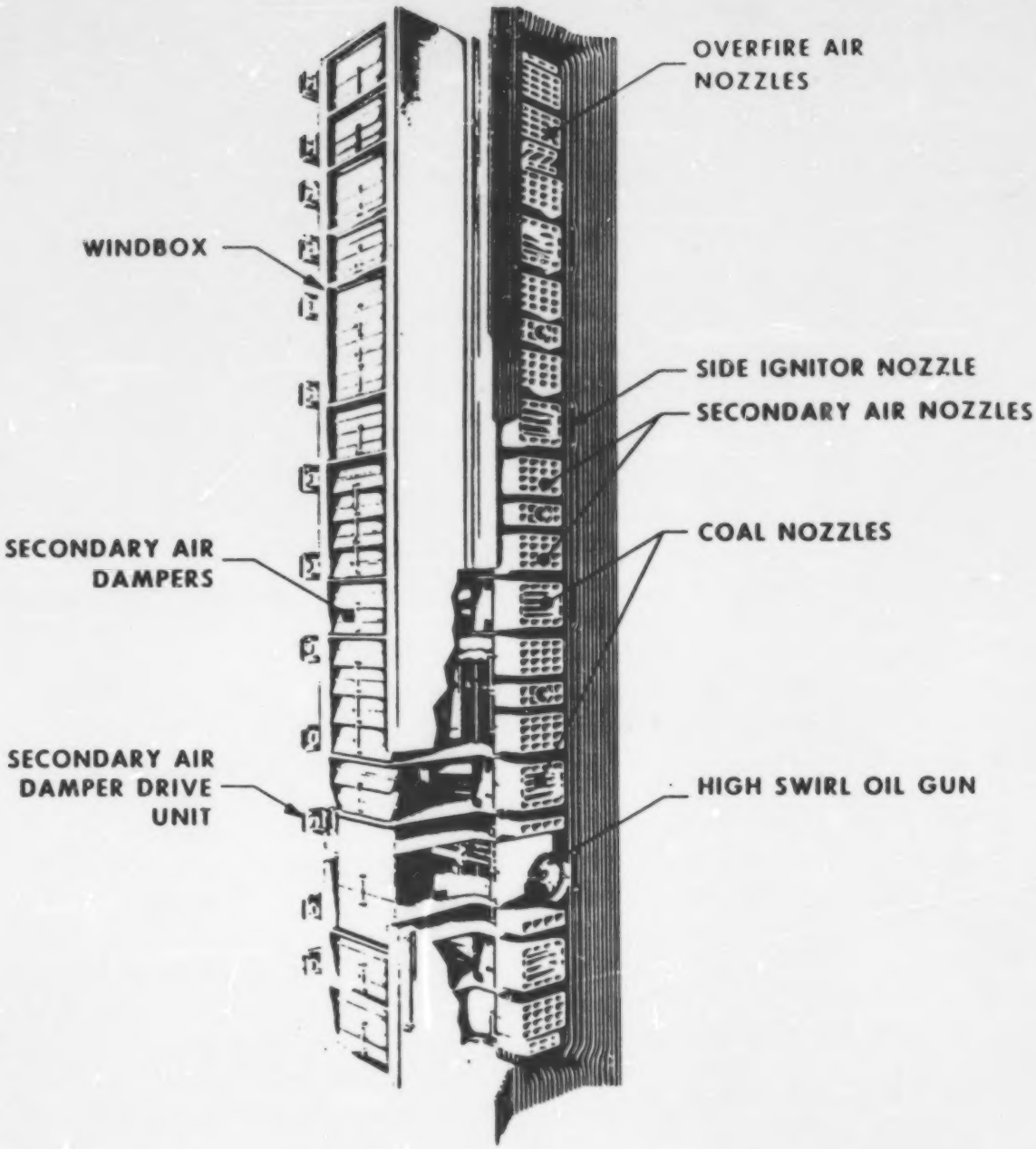

Figure 1-4. Vertical Arrangement of Tangentially Firing Burners

automatically tilted up to reduce the amount of surface area exposed to the combustion gases. This decreases the overall furnace heat absorption and maintains exit gas temperatures.

The implementation of RDF co-firing is similar to that in wall fired boilers. RDF injectors are required as well as drop grate installation to ensure complete burnout of large RDF particles. The RDF injectors are typically located above the coal nozzles.

1.2.2.4 Cyclone Fired Boiler

A schematic of a typical cyclone fired furnace is shown in Figure 1-5.[2] The coal is fired into a water cooled horizontal cylinder in which the volumetric heat release rate is extremely high. Crushed coal is introduced at one end of the cylinder. About 20 percent of the combustion air, termed primary air, is introduced tangentially to the burner and imparts a whirling motion to the coal. Secondary air is introduced through the top of the cylinder in the same tangential direction imparting further whirling motion. The cyclone typically operates at temperatures exceeding 3000°F (1649°C). These temperatures are sufficient to melt the ash into a liquid slag which forms a layer on the walls of the cylinder. Most of the incoming coal is thrown against the wall and is caught in the slag layer where it burns rapidly. Excess slag continually drains through a slag tap in the end of the cylinder and is quenched to form the "bottom ash." Approximately 60 percent of the ash is caught in the slag layer and forms bottom ash. The other 40 percent is entrained and carried through the convection section. RDF is typically introduced through the secondary air ports. No other modifications are needed to co-fire RDF in a cyclone boiler.

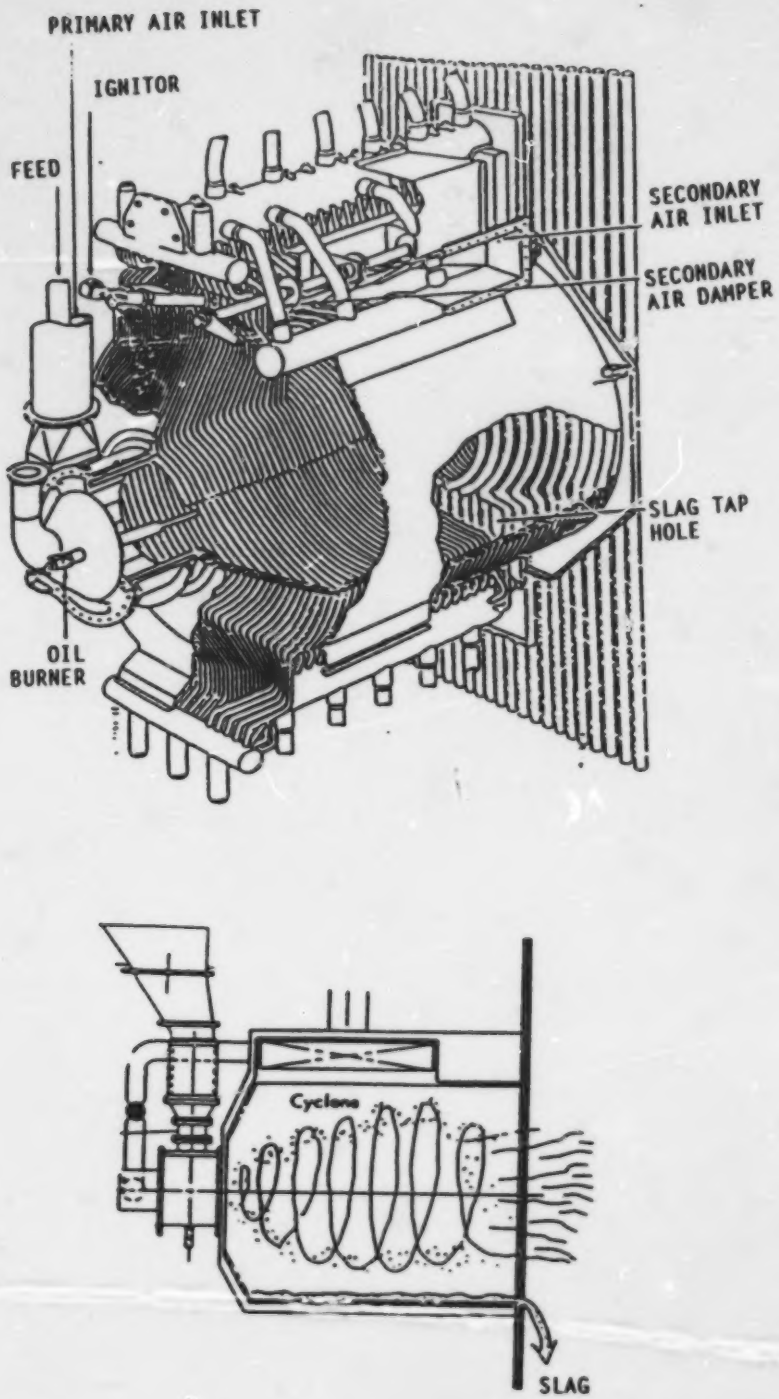

Figure 1-5. Typical Cyclone Fired Furnace

2.0 POPULATION DESCRIPTION

The following population description includes coal fired boilers that currently co-fire RDF, units that previously co-fired RDF but have ceased to do so, RDF co-firing demonstration projects, and the projected new co-firing facilities.

2.1 Currently Operating RDF Co-Fired Facilities

Six utility boilers located in four different facilities currently co-fire RDF. The facilities are Madison Gas and Electric's Blount Street Power Plant; the City of Ames, Iowa's municipal power plant; Baltimore Gas and Electric's C.P. Crane Station; and the City of Lakeland, Florida's McIntosh Power Plant. The power plants range in capacity from 35 MW_e to 364 MW_e and co-fire from 1 to 20 percent RDF by weight (0.5 to 13 percent of total heat input). The design and operating characteristics of the boilers are summarized in Table 2-1.[1,4,5]

2.1.1 Blount Street Power Plant, Madison, Wisconsin

The Blount Street Power Plant is owned and operated by Madison Gas and Electric Company. Two 50 MW_e boilers located at the power plant have been modified to co-fire RDF. The boilers, originally installed in 1957 and 1961, are the oldest units in which RDF is co-fired. Both were modified to co-fire RDF in 1975. Both boilers are Babcock and Wilcox front wall fired pulverized coal units equipped with burners at three elevations. The RDF injectors are installed between the bottom two burner levels. A drop grate was added to the boilers to ensure complete burnout of the ash generated by the RDF. A schematic of one of the modified boilers is shown in Figure 1-3. Each of the units is equipped with an ESP to control particulate emissions.

The RDF used in the two boilers is produced off-site by the City of Madison. The RDF processing plant includes a primary shredder, a magnetic separator, a screen (to remove glass and dirt), a secondary shredder, and an air sweep classifier. The resulting RDF has a nominal particle size of 3/4 inch (0.02 m), an ash content of 9 to 14 weight percent on a wet basis, and a moisture content of 20 to 30 percent. The as-fired heat content of the RDF reportedly ranges from 7000 to 8400 Btu/lb (1.63×10^7 to 1.95×10^7 J/kg). On the average, 90 tons (82 tonnes) per day of RDF is co-fired in each of the

TABLE 2-1. SUMMARY OF UNIT CHARACTERISTICS

Plant	Madison, WI (Blount)	Madison, WI (Blount)	Ames, IA	Ames, IA	Baltimore (Crane)	Baltimore (Crane)	Lakeland, FL (McIntosh)
Unit	8	9	7	8	1	2	3
Unit Capacity	50	50	35	65	200	200	364
Boiler Mfr	B&W	B&W	CE	B&W	B&W	B&W	
Coal Firing Method	Pulverized Coal Front-Fired (Suspension)	Pulverized Coal Front-Fired (Suspension)	Pulverized Coal Tangential (Suspension)	Pulverized Coal Direct Fired (Suspension)	Cyclone	Cyclone	Opposed Pulverized Coal (Suspension)
Dump Grate	Y	Y	Y	Y	N	N	Y
RDF Mass Input Avg (tpd)	90	90	115.4	252	125-200	125-200	62
(%)	15	15	18	20	5-10	5-10	1
Boiler Start Date	1957	1961	1967	1982			1982
Co-Firing Start Date	1975	1975	1976	1982	1986	1980	1982
APCD	ESP	ESP	ESP	ESP	Baghouse	Baghouse	ESP, Wet Scrubber
Particulate Emissions	-	-	0.157 gr/dscf	0.020 gr/dscf	-	- lb/MMBtu	0.09
RDF Injection Location	Between 2 lower coal	Just above primary comb. zone	Just above primary comb. zone	Just above primary comb. zone	In cyclone burner	In cyclone burner	Even with top coal but on side wall
RDF size (in.)	0.75	0.75	1.5	1.5	-	-	2

two boilers. This is approximately 15 percent by weight of the fuel used by the boilers (12 percent of total heat input).

Madison Gas and Electric has not reported any major problems co-firing RDF in their boilers.[6] They have minor problems with the formation of clinkers which solidify on the grate and must be removed by hand. Despite the lack of firing problems, they report that the additional operating costs associated with co-firing RDF make it uneconomical without special price concessions and subsidies from the City. The price which Madison Gas and Electric pays to the City for the refuse is based on the price which they have to pay for coal, less any operating expenses related to burning RDF.[2]

2.1.2 Ames City Power Plant, Ames, Iowa

The Ames City Power Plant is owned and operated by the City of Ames, Iowa. Two boilers at the facility have been modified to co-fire RDF with coal. Unit 7 is a 35 MWe Combustion Engineering tangentially fired pulverized coal boiler originally installed in 1967 and modified to burn RDF in 1976. Unit 8 is a 65 MWe Babcock and Wilcox front wall fired pulverized coal unit originally designed to burn RDF and installed in 1982. Air transport RDF injectors on both units are located just above the primary combustion zone. In addition, both units are equipped with drop grates to insure complete burnout of the ash produced by the RDF. A diagram of Unit 7 is shown in Figure 2-1.[2] The boilers are both equipped with ESPs. The ESP at Unit 7 has two fields and operates at 390°F (199°C), and the ESP at Unit 8 contains eight fields and operates at 660°F (349°C).

The RDF used at the Ames facility is produced off-site by the city. Processing includes primary shredding, separation of ferrous metals, separation of glass and grit, secondary shredding and air classification. The resulting RDF has a nominal particle size of 1.5 inches (0.04 m). The RDF has an average ash content of 12 percent and an as-fired heat content of 6200 Btu/lb (1.44×10^7 J/kg). Unit 7 is designed to fire 544.8 tpd (494 tonnes/day) coal and 115.4 tpd (105 tonnes/day) RDF (around 18 percent by weight RDF, or about 12 percent of total heat input). Unit 8 is designed to fire 1128 tpd (1023 tonnes/day) coal and 282 (256 tonnes/day) RDF (about 20 percent by weight RDF or about 10 percent of total heat input). The Ames facility operators report that a total of 44,275 tons (40,157 tonnes) of waste were burned in the two units in 1987.

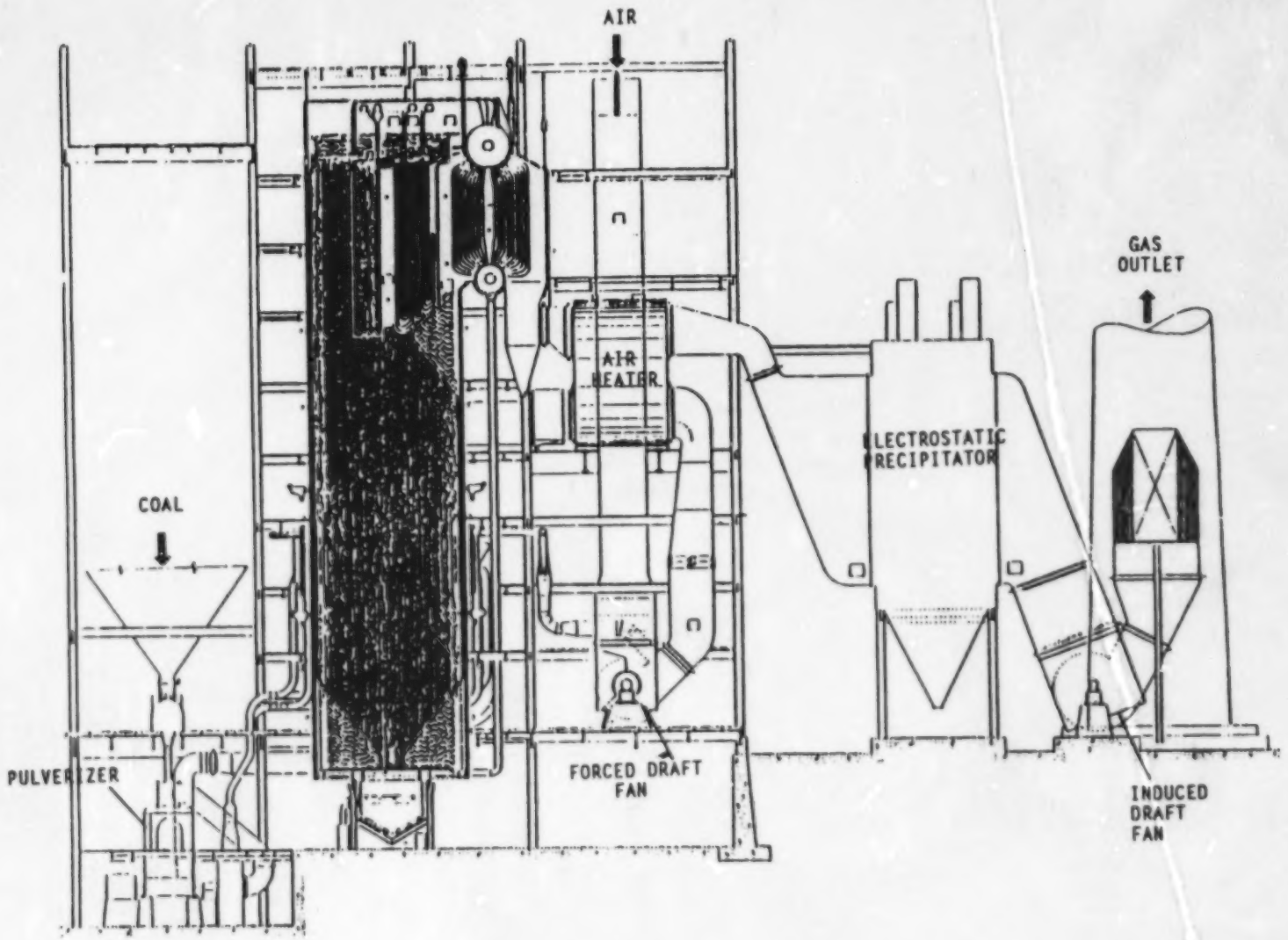

Figure 2-1. Profile of Ames, Iowa's Unit 7

The operators of the Ames facility have experienced considerable difficulty firing RDF.[7] They report the primary problems are related to handling the RDF feed and the resulting ash. The variable nature of RDF makes it difficult to maintain continuous feed with a relatively constant heat content. Wires and non-ferrous metals create significant ash handling problems at the Ames facility. The RDF feeding system frequently jams causing damage to the machinery. Originally, tube wastage was observed around the drop grate. The operators speculate that the wastage was caused by the reducing atmosphere produced by ash burning on the grate. This problem was remedied by installing refractory around the grate. The plant operators report that RDF co-firing in their boilers is not a financially advantageous process because of high maintenance costs.

2.1.3 C.P. Crane Station, Middle River, Maryland

Baltimore Gas and Electric Company operates the C.P. Crane power station. The station has two 200 MW e Babcock and Wilcox cyclone fired boilers. Unit 2 was modified to co-fire RDF in 1980 and Unit 1 began co-firing RDF in 1986. The modifications involved installation of RDF injection equipment in the cyclone. Initially, erosion was observed on the cyclone wall opposite the RDF injection port. The installation of a deflection plate eliminated the problem. The units are equipped with a baghouse to control particulate emissions.

The RDF fired at the C.P. Crane facility is produced off site (12 miles [19,311 m] from Crane Station) by National Ecology. RDF processing includes shredding, ferrous metal recovery, and screening. The resulting RDF has a nominal size of less than 2 inches (0.05 m). RDF comprises an average of 5 to 10 percent by weight (3 to 5 percent total heat input) of the total fuel fed to the boiler, approximately 125-200 tpd (113-181 tonnes/day) of RDF.

Baltimore Gas and Electric reports having no major problems operating with RDF.[8] The fly ash produced is used as structural fill for an industrial park and the bottom ash is sold for use in sand blasting. The utility has not yet identified the impact of firing RDF on operating and maintenance costs; however, they report that, from a fuel cost standpoint RDF co-firing is a financially attractive activity. The RDF purchase contract requires the utility to pay only 80 percent of the price they would pay for an equivalent

amount of coal (on a heating value basis), resulting in a fuel cost savings of 20 percent.[2]

2.1.4 McIntosh Power Plant, Lakeland, Florida

The McIntosh Power Plant is operated by the City of Lakeland and owned by the city in conjunction with Orlando Utilities. One of the boilers at the facility was installed in 1982 and was designed to co-fire RDF and coal. The unit is a 364 MWe Babcock and Wilcox opposed burner, pulverized coal fired boiler and contains coal burners located at four elevations on the front and rear walls. Two air transport RDF injectors are located on each side wall at the same elevation as the upper coal burners. The boiler is also equipped with drop grates. A wet scrubber followed by an ESP provide control of stack emissions. The ESP contains five fields and operates at about 282°F (139°C).

The RDF burned at the McIntosh Power Plant is prepared on-site by the city, has a nominal size of 2 inches (0.05 m) and has an average as-fired heat content of 4500 Btu/lb (1.05×10^7 J/kg). Only 1 percent of the mass fired in the boiler is made up of RDF. However, this amounts to nearly 24,000 tons (21,768 tonnes) of waste in 293 operating days in 1987 (approximately 82 tpd [72 tonnes/day]).

Lakeland reports having no problems operating the McIntosh plant.[9] The plant operators have not seen any excess tube wastage, slagging or fouling in the five years the plant has operated with RDF. They report that firing RDF appears to be financially viable when operating costs alone are considered. However, when debt retirement on the processing plant is also considered, the unit does not quite break even.

2.1.5 Summary

Two fundamentally different types of coal fired boilers are used in the existing population. The Baltimore Gas and Electric unit is a cyclone fired boiler while the other plants use pulverized coal fired boilers. The operating co-fired boilers range in size from 35 MWe to 364 MWe. Fluff RDF (f-RDF) is used in all of the operating plants. Nominal sizes range from 0.75 inch to 2 inches (0.02-0.05 m). The amount of RDF co-fired ranges from 1-20 percent by weight and from 0.5-12 percent on a heat input basis.

2.2 Facilities Which Have Ceased Co-Firing RDF

Information is available on the operation of six facilities which previously co-fired RDF but have discontinued this practice. These facilities are Oscar Mayer Corporation's Madison Packing Plant; Union Electric, St. Louis; Wisconsin Electric in Milwaukee; Rochester Gas and Electric in New York; Commonwealth Edison in Chicago; and United Illuminating in Bridgeport, Connecticut. Individual boiler design and operating characteristics are summarized in Table 2-2.1.5.10

2.2.1 Oscar Mayer Steam Generating Plant, Madison, Wisconsin

The boiler is owned and operated by Oscar Mayer Corporation. The steam generated by the boiler is used as either process steam or to generate electricity. The boiler has a capacity of 125,000 pounds of steam per hour (56,699 kg/hr) and was originally installed in 1949. The unit consists of a Wicks spreader stoker boiler and a Detroit Stoker traveling grate system. The Oscar Mayer boiler was modified to burn RDF in 1979 and ceased firing RDF in 1986. A series of cyclones were used to control particulate emissions.

The RDF used by Oscar Mayer was generated by the City of Madison and is identical to that used by Madison Gas and Electric at the Blount Street Power Plant. The Oscar Mayer facility had a capacity to burn up to 60 tons (54 tonnes) of RDF per day.

Oscar Mayer reports that there was little economic incentive to continue co-firing RDF. They found overhead and maintenance costs to be prohibitive. In addition, the quality of the RDF varied excessively for convenient use. However, the facility still has the capacity to co-fire RDF should the economic situation change.

2.2.2 Union Electric, St Louis

Units 1 and 2 at the Meramec Plant are owned and operated by Union Electric. They are both 125 MWe Combustion Engineering, tangentially fired pulverized coal boilers which began initial operation in 1953. Both units were modified to co-fire RDF in 1972 and ceased co-firing in 1975. There are four vertically arranged, tilting coal burners in each corner. RDF injectors were installed, one in each corner between the second and third coal burners.

TABLE 2-2. SUMMARY OF CHARACTERISTICS OF BOILERS WHICH HAVE CEASED FIRING RDF
PAGE 1 OF 2

PLANT	UNIT NO.	CAPACITY (MWe)	BOILER MFR	PRIMARY FUEL FIRING METHOD	DUMP GRATE	RDF MASS INPUT AVERAGE tpd	tonnes/day	%
Madison, WI (Oscar Mayer)	5	*	Wicks	Traveling Grate Spreader Stoker	N	60	54	30
St. Louis	1	125	CE	Pulverized Coal	N	315	286	20
	2	125	CE	Tangential (Suspension)	N	315	286	20
Milwaukee	7	310	CE	Pulverized Coal	N	1100	998	30
	8	310	CE	Tangential (Suspension)	N	1100	998	30
Rochester	1	42	CE	Pulverized Coal	Y	100	91	23
	2	62	CE	Tangential	N	150	136	23
	3	62	CE	(Suspension)	Y	150	136	23
	4	75	CE	(all 4 units)	N	175	159	23
Chicago	7	200	CE	Pulverized Coal	N	440	399	16
	8	315	CE	Tangential (Suspension)	N	690	626	16
Bridgeport	1	80	B&W	No. 6 Fuel Oil Cyclone	N	380	345	50

*125,000 lb steam/hr (56,699 kg steam/hr)

TABLE 2-2. SUMMARY OF CHARACTERISTICS OF BOILERS WHICH HAVE CEASED FIRING RDF
PAGE 2 OF 2

PLANT	UNIT NO.	BOILER START DATE	CO-FIRING START DATE	APCD	ASH DISPOSAL	PARTICULATE EMISSIONS	RDF INJECTION LOCATION	RDF SIZE (in)	RDF SIZE (m)
Madison	5	1949	1979	Multiple Cyclones	Off-site landfill	-	-	0.75	0.02
St. Louis	1 2	1953	1972	ESP	Ponds	.315 g/dncm	Between 2nd & 3rd level of coal burners	1.5	0.04
Milwaukee	7 8	1967	1977	ESP	Landfill	-	Above coal burners	1.0	0.03
Rochester	1 2 3 4	1942 1962 1962 1975	1981 1981 1981 1981		Landfill	-	Above coal burners	1.0	0.03
Chicago	7 8	1958 1961	1978 1978	ESP	Landfill	-	Above coal burners	1.5	0.04
Bridgeport	1	1958	1979	ESP	Landfill	-	Through primary air duct	0.003	7.6×10^{-5}

Dump grates were not added. An electrostatic precipitator was used to control particulate emissions.

The RDF was generated by the City of St. Louis at a processing facility 18 miles (28,967 m) from the Meramec Plant. The processing plant used a primary shredder, ferrous magnets, and an air classifier. The resulting RDF had a nominal size of 1.5 inches (0.04 m), an average ash content of 19.2 percent, and an as-received heat content of 4900 Btu/lb (1.14×10^7 J/kg). The facility was able to burn 49,000 tons (44,443 tonnes) from 1972 to 1975, with an average RDF heat input of 10 percent (approximately 315 tpd [286 tonnes/day] of RDF).

Problems experienced at Meramec included plugging and jamming of the RDF feed system and excessive abrasion of RDF feed particles due to the high glass and grit content of the RDF. The excessive abrasion caused frequent leaks in the feed lines which had to be continually repaired resulting in extremely high maintenance costs. Boiler efficiency was decreased due to the higher moisture and ash content of RDF compared to coal and increased unburned combustibles in the bottom ash.

2.2.3 Wisconsin Electric, Milwaukee

Units 7 and 8 at Wisconsin Electric's Oak Creek Station are both 310 MWe Combustion Engineering, tangentially fired pulverized coal boilers. These units entered commercial service in 1967 and were modified to co-fire RDF in 1977. RDF co-firing ceased in 1980. There are five tilting coal burners in each corner. Four RDF injectors were installed, one in each corner, above the top coal burners. No dump grates were added.

The RDF was generated by the American Can Company processing plant approximately 20 miles (32,185 m) from the Oak Creek Station. The plant included primary and secondary shredders, ferrous and aluminum separation, screens, and an air classifier. The resulting RDF had a nominal size of 1.0 inch (0.03 m), an ash content of 19 percent, and an as received heating value of 5200 Btu/lb (1.21×10^7 J/kg). The facility was able to burn 100,000 tons (90,700 tonnes) of RDF in 3-1/2 years. The RDF supplied an average of 15 percent of the total heat input (approximately 1100 tpd [998 tonnes/day] of RDF).

The Oak Creek Station experienced excessive abrasion of the RDF feed lines because of the glass and grit in the RDF. Increased slagging also resulted from co-firing RDF. Solidified slag collected at the bottom of the furnace and choked off bottom ash flow. Deslagging involved the use of shotguns and dynamite to blast loose slag deposits and required 4-5 hours. Deslagging was required 12-15 times per month during co-firing as opposed to 7-10 times per month during operation with coal alone.

2.2.4 Rochester Gas and Electric, New York

The Russell Station Units 1, 2, 3, and 4, owned and operated by Rochester Gas and Electric, are Combustion Engineering, tangentially fired, pulverized coal boilers with capacities of 42 MWe, 62 MWe, 62 Mwe, and 75 MWe, respectively. Unit 1 began commercial operation in 1949 followed by Units 2, 3, and 4 in 1951, 1953, and 1957, respectively. All began co-firing RDF in 1981 and ceased co-firing in 1983. Two RDF injectors were installed in each unit in opposite corners above the coal burners. Units 1 and 3 received dump grates; Units 2 and 4 did not.

RDF was generated at a processing plant owned by Monroe County, NY located 8 miles (12,874 m) from Russell Station. The facility includes primary and secondary shredders, ferrous and aluminum separation, screens, and an air classifier. The RDF had a nominal size of 1 inch (0.03 m), a 12 percent ash content, and an as-received heating value of 7850 Btu/lb (1.82×10^7 J/kg). Russell Station was able to burn 12,000 tons (10,884 tonnes) in 1.2 years. The RDF supplied an average of 15 percent of the total heat input which is approximately 100 tpd (91 tonnes/day), 150 tpd (136 tonnes/day), 150 tpd (136 tonnes/day), and 175 tpd (159 tonnes/day) of RDF co-fired in Units 1, 2, 3, and 4, respectively.

Problems experienced at the Russell Station facility included pluggage of RDF feed lines and large clinker formation on dump grates in Units 1 and 3. Boiler efficiency decreased because of the higher moisture and ash content of RDF compared to coal, increased excess air levels, and increased amounts of unburned combustibles in bottom ash.

2.2.5 Commonwealth Edison, Chicago

Units 7 and 8 at Crawford Station are owned by Commonwealth Edison of Chicago. Unit 7 is a 200 MWe Combustion Engineering, tangentially fired pulverized coal boiler, which entered commercial service in 1958. Unit 8 is of the same configuration, but larger (325 MWe), and was brought on line in 1961. Both units were modified to co-fire RDF in 1978 and ceased co-firing in 1979. The modifications included installation of 2 RDF injectors in two opposite corners of each furnace (4 per unit). Dump grates were not installed.

The RDF was provided by the city of Chicago processing plant which includes primary and secondary shredders, ferrous magnets, and an air classifier. The nominal size of the RDF was 1.5 inches (0.04 m). The as-received heat content was 5600 Btu/lb (1.30×10^7 J/kg) with an ash content of 17 percent. Crawford Station was able to burn 20,000 tons (18,140 tonnes) of RDF in 1.3 years. The average heat input provided by the RDF was 10 percent, approximately 440 tpd (399 tonnes/day) of RDF for Unit 7 and 690 tpd (626 tonnes/day) of RDF for Unit 8.

Problems at the Crawford Station included plugging and excessive abrasion of the RDF feed lines, increased volume and particle size of bottom ash, and increased slag accumulation.

2.2.6 United Illuminating, Bridgeport, Connecticut

Unit 1 at Harbor Station is owned by United Illuminating of Bridgeport, Connecticut. This Babcock and Wilcox 80 MWe cyclone boiler entered commercial service in 1958 as a coal-fired unit. In 1968, it was converted to burn No. 6 fuel oil. RDF co-firing began in 1979 and ceased in 1980. RDF was injected through the primary air duct to the furnace. An electrostatic precipitator was used to control particulate emissions.

Harbor Station received RDF from a processing plant owned and operated by Combustion Equipment Associates (CEA), Occidental Petroleum Corporation, and the Connecticut Resources Recovery Authority. The plant includes a primary shredder, ferrous and aluminum separation, screens and an air classifier. The resulting RDF was a dry powder with an ash content of 15 percent and a heat content of 7800 Btu/lb (1.81×10^7 J/kg). A total of 7900

tons (7165 tonnes) of RDF were co-fired over a two year period providing an average heat input of 30 percent (approximately 380 tpd [345 tonnes/day] of RDF).

There were no major problems associated with co-firing RDF at the Bridgeport Harbor Station. The facility ceased co-firing because the RDF processing plant closed (mainly due to CEA's lack of operating funds).

2.3 RDF Co-Firing Demonstration Projects

Information is available regarding the experiences of two facilities involved in RDF co-firing demonstration projects. These facilities are the Atlantic Electric's B.L. England Station in Beesley's Point, NJ and the Milwaukee County, WI Institution's Power Plant. The boiler design and operating characteristics are summarized in Table 2-3.[11,12]

2.3.1 B.L. England Station, Beasley's Point, New Jersey

The B.L. England Station is owned and operated by Atlantic Electric Company.[11] One of the boilers at the station is a 129 MWe Babcock and Wilcox cyclone fired unit which was used to co-fire RDF as part of a feasibility demonstration study in 1987. The RDF was injected through the secondary air ducts in the cyclone. The unit is equipped with an electrostatic precipitator to control particulate emissions. RDF was co-fired at the facility only during an 18-day test program.

RDF was supplied to the boiler by National Ecology Incorporated (NEI), which operates an RDF processing plant in Cockeysville, Maryland. The RDF had an average ash content of 9.1 percent and as-received heat content of 5,900 Btu/lb (1.4×10^7 J/kg). The facility was able to burn 2550 tons (2313 tonnes) of RDF during the 18-day test program, approximately 142 tpd (129 tonnes/day). Stable operation was maintained only when RDF composed less than 15 percent of the total heat input to the boiler.

Severe fouling and slagging problems were experienced during the co-firing tests. The air heater plugged rapidly and forced a shut down of the unit. In addition, a hard tenacious ash that could only be removed with jackhammers fouled the reheater surfaces. Unit efficiency was significantly affected by RDF co-firing. The unit gradually derated from 129 MWe to 100 MWe.

TABLE 2-3. SUMMARY OF BOILER CHARACTERISTICS FOR UNITS INVOLVED IN RDF CO-FIRING DEMONSTRATION PROJECTS

Plant	Beasley's Point, NJ	Institutions Power Plant Milwaukee County, WI
Unit No.	1	3
Unit Capacity	129 MWe	110,000 lb steam/hr (49,895 kg steam/hr)
Boiler Mfr	B&W	Union Iron Works
Coal Firing Method	Cyclone	Traveling Grate Spreader Stoker
Dump Grate	N	N
RDF Mass Input Avg	142 tpd 129 tonnes/day 5-20%	21%
Boiler Start Date		1954
Co-Firing Start Date	1981	1987
APCD	ESP	ESP
RDF Injection Location	Secondary air duct	
RDF Size		3/4 inch (0.02 m)

Emissions increased significantly when co-firing RDF. Particulate emissions and precipitator power levels increased by a factor of three. Because of these problems, Atlantic Electric concluded that RDF co-firing was an unacceptable process.

2.3.2 Milwaukee County, WI Institutions' Power Plant

The County Institutions' Power Plant is owned and operated by Milwaukee County, WI. One of the boilers at the plant is a Union Iron Works spreader stoker rated at 110,000 pounds of steam per hour (49,895 kg/hr). The unit is equipped with a three-field ESP. RDF was co-fired during the test program for a total of 9 days with performance testing conducted for 3 days in 1981.

The RDF was supplied by the American Can Company located in Milwaukee with a nominal size of 3/4-inch (0.02 m), an ash content of 18 percent, a moisture content of 20 percent, and a heating value of approximately 5900 Btu/lb (1.4×10^7 J/kg). During testing, the RDF composed approximately 21 percent by weight of the coal/RDF mixture and approximately 11 percent by heating value.

No significant feeding problems were encountered during testing. However, once in the furnace, the coal/RDF mixture tended to clinker more frequently than coal alone. Also, some RDF fell into the ash pit unburned. During testing, the boiler was unable to achieve steam generation rates that had been easily attained when firing coal alone. This was reportedly due to the volumetric limitations of the spreader feeder equipment when firing the less dense coal/RDF mixture. In addition to reduced steam production, erratic steam rates were experienced as well. This was reportedly due to non-uniform mixing of the coal and RDF. Particulate carryover reportedly did not significantly increase. This was reportedly due to using densified RDF as opposed to fluff RDF.

2.4 Projected New Population

There are no known existing utility boilers that are planning modifications to co-fire RDF. There are no known plans to construct new facilities with the capability to co-fire RDF.

3.0 IMPACT OF RDF CO-FIRING ON BOILER PERFORMANCE

RDF co-firing affects many aspects of boiler operation and performance. A 1986 Electric Power Research Institute (EPRI) study assessed the impacts of RDF co-firing on boiler operating and performance parameters, including:[13]

- Boiler efficiency
- Flue gas flow rates
- Stack emissions
- Bottom ash production
- Slagging and fouling

Boiler efficiency is defined as the fraction of the energy introduced into the furnace that is recovered in the boiler and other heat recovery equipment. Boiler efficiency decreases with RDF co-firing because of increased flue gas production, increased unburned carbon, and fuel moisture losses. The increased flue gas production results in part from the increase in combustion air required for RDF co-firing. The additional air exiting the unit carries with it some of the heat that would otherwise have been used to generate steam. Unburned carbon represents potential energy that is not liberated. Any moisture in the waste evaporates by absorbing heat that might otherwise be used to generate steam.

As shown in Table 3-1, the Milwaukee County Institutions' Power Plant test data are consistent with the EPRI assessment.[12] The boiler efficiency decreased from 89 percent to 85 percent when co-firing 21 percent by weight RDF (11 percent by heating value) as compared to coal alone. The flue gas generated per pound of steam produced increased slightly for the coal/RDF mixture. The amount of combustible material in the ash was greater for the mixture as well. Table 3-1 also shows that the moisture content of the coal/RDF mixture is greater than the moisture content of the coal alone.

The EPRI report states that flue gas flow rates increase as the amount of RDF co-fired increases. This is primarily due to the requirement for increased excess air to account for variability in RDF feeding. The stoichiometric combustion air requirements for a typical high volatile bituminous coal and a typical RDF are approximately equal on a heating value basis. When RDF supplies 20 percent of the heat input to the boiler, the volumetric flow rate of air leaving the air heater increases from 17 to 20

TABLE 3-1. TEST DATA - MILWAUKEE COUNTY INSTITUTIONS' POWER PLANT COAL/D-RDF CO-FIRING PROJECT

	COAL	COAL/D-RDF
Boiler Efficiency (%)	88.9	85.1
Flue Gas Produced (lb/hr) / Steam Produced (lb/hr)	2.226	2.280
% Combustible:		
Bottom Ash	2.2	2.8
Fly Ash	28.1	29.1
% in Feed:		
H_2O	5.90	8.31
Cl	0.18	0.24
S	2.07	1.79
N	1.12	0.99
Ash	10.28	11.38
Stack (lb/10^6 Btu):		
HCl	0.063	0.206
SO_2	2.96	2.97
NO_2	0.44	0.49
Particulate	0.090	0.063
Resistivity - ESP Inlet (10 Ω-cm)	6.06	12.9
ESP Efficiency (%)	84.01	83.79

percent over the coal-only firing. This increased air flow not only causes additional energy losses through the stack, but may impact the maximum achievable load due to fan capacity.

Co-firing can affect the emissions of both particulates and acid gases (SO_x and HCl). Table 3-2 summarizes the characteristics of a typical high volatile bituminous coal and a typical RDF.[14,15] Compared to coal, RDF typically has low sulfur concentrations, high chlorine concentrations, and a high ash content. The data in Table 3-1 also show a lower sulfur content, higher chlorine content and a higher ash content in the coal/RDF mixture as compared to coal alone. Thus, co-firing RDF typically increases HCl emissions and decreases SO_x emissions. In general, particulate emissions increase with RDF co-firing. As shown in Table 3-1, the HCl emissions did increase in the Milwaukee County test. However, the SO_2 emissions remained the same and the particulate emissions actually decreased. It should be noted that the test was conducted with densified RDF which tends to create less particulate than fluff RDF. According to the EPRI report, fly ash resistivity appears to increase when RDF is co-fired. This increased resistivity combined with increased flue gas volume may decrease ESP efficiency.[13] This is consistent with the data in Table 3-1 that show the resistivity double with RDF co-firing and a corresponding decrease in ESP efficiency from 88.9 percent for coal alone to 85.1 percent with the coal/RDF mixture.[12]

CO emissions from RDF co-firing with coal are expected to be in the same range as for coal firing alone (see Figure 3-1).[10] CO emissions from RDF co-fired systems will be dependent, however, on the same factors that impact CO production in conventional fuel fired systems: low excess air or poor fuel/air mixing causing local or overall fuel rich conditions, high excess air causing reduced gas temperatures which quenches combustion reactions, and poor fuel preparation and/or feeding leading to insufficient burning time. RDF co-fired systems are somewhat more susceptible to failures by some of these mechanisms, due to the heterogeneity of RDF and the difficulty associated with uniform RDF introduction to the combustor. When system design and operation are sufficient controlled to account for these factors, CO emissions comparable to coal-fired systems can be achieved with co-fired systems.

NO_x emissions from RDF co-fired systems are not expected to be significantly different than those from coal-fired systems. NO_x is formed

TABLE 3-2. COMPARISON OF TYPICAL COAL AND RDF COMPOSITION*

	COMPOSITION, PERCENT	
	COAL‡	RDF
Moisture	2.5	25.2
Carbon	75.0	33.8
Hydrogen	5.0	4.5
Nitrogen	1.5	0.5
Oxygen	6.7	27.9
Sulfur	2.3	0.2
Chlorine	0.0	0.39
Ash	7.0	7.51
Btu/lb	13000.0	6000.0
J/kg	3.0×10	1.4×10^7

*References 14, 15

‡Pittsburgh seam coal, West Virginia

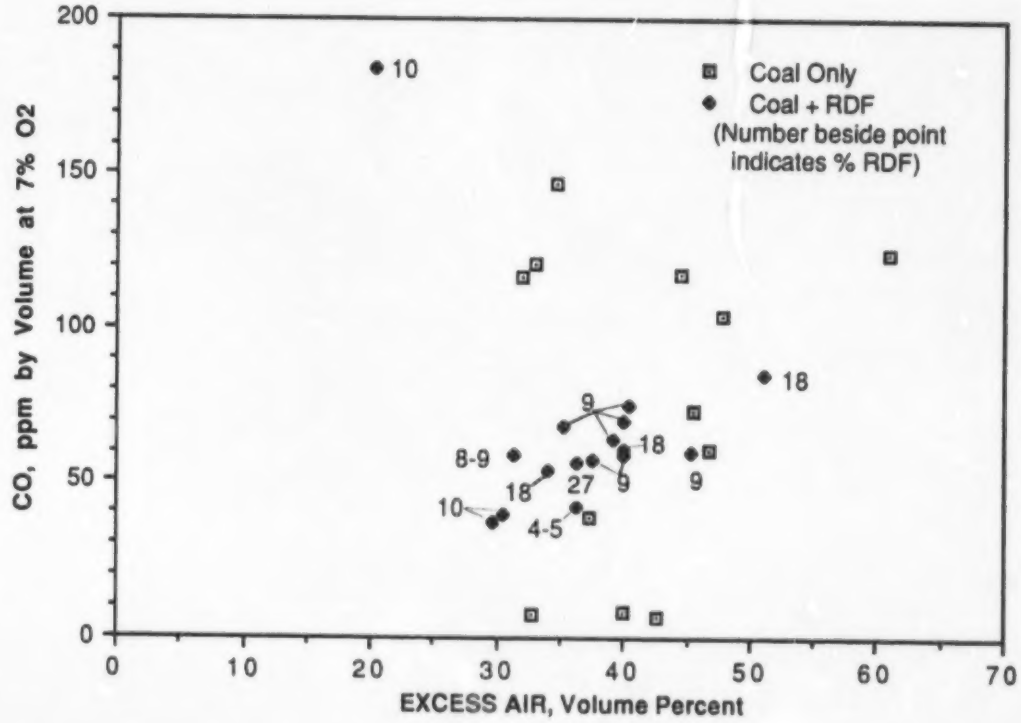

Figure 3-1. Effect of Excess Air on CO Emissions at St. Louis Utility Boiler

during combustion by two mechanisms: oxidation of fuel-bound nitrogen (approximately 75 percent of the total NOx formed) and thermal fixation of nitrogen from the combustion air.[16] Fuel NOx formation is dependent on the fuel nitrogen content and the local stoichiometry when the nitrogen is evolved, but is relatively insensitive to temperature. Thermal NOx formation is strongly temperature dependent. Table 3-2 indicates that the nitrogen content of RDF is typically lower than that of coal. However, the local fuel rich conditions at the point of fuel introduction that are the basis for low fuel NOx formation in advanced coal-fired systems are to be avoided in RDF systems since they have been linked to the formation of trace organic species. Thus, these two factors that influence fuel NOx formation will have conflicting effects, leading to the conclusion that fuel NOx emissions will not be significantly affected. Thermal NOx formation is not directly impacted by the fuel. However, the increased excess air requirement associated with RDF co-firing and the attendant decrease in gas temperature will likely result in a slight decrease in thermal NOx emissions, especially at relatively low co-firing rates where the effects of the predominant fuel are expected to dominate. This is consistent with the Milwaukee County data in Table 3-1 where NO2 emissions increased only slightly with the coal/RDF mixture as compared to the coal alone.

The only dioxin data available on co-fired units were obtained in 1983 during a detailed study of Unit 7 at the Ames facility co-firing about 20 percent RDF by weight.[4] No dioxins or furans were detected in the emissions. The detection limit for CDD and CDF in the composite flue gas extracts was 0.1 to 0.25 ng/dscm. In addition, emissions tests have been performed at seven coal fired boilers. No CDD or CDF emissions were detected from any of these facilities. These reports are presented in the National Dioxin Study Tier IV Project Summary Report.[17]

The available emissions data from boilers burning 100 percent RDF indicate that highly variable CDD/CDF emissions may occur under normal operating conditions.[14] It can be assumed that a co-fired system could also produce measurable quantities of CDD/CDF under conditions where RDF comprises a large portion of total heat input to the boiler. However, these conditions are usually restricted due to operational limitations imposed by required steam temperatures and pressures needed for electrical generation. As a result, the conditions under which substantial CDD/CDF emissions occur are not expected to be encountered under normal operation in an RDF co-fired system.

result, the conditions under which substantial CDD/CDF emissions occur are not expected to be encountered under normal operation in an RDF co-fired system.

Bottom ash production increases by a factor of 2 or 3 when 10-20 percent RDF is co-fired on a heat input basis because RDF has a higher specific ash content (lb/Btu) than coal.

Slagging and fouling potential is an important consideration in coal fired boilers. Increased slagging or fouling increases maintenance costs, decreases boiler efficiency and decreases boiler availability. The slagging and fouling potential is a function of the composition of the ash. A number of parameters have been developed to quantify the slagging and fouling potential of a given ash. Slagging potential is indicated by the fusion temperature of the ash while fouling potential can be quantified through the use of the "fouling index." The fouling index is defined as the product of the base to acid ratio and the concentration of Na_2O in the ash. Typical RDF fusion temperatures are around 2190 to 2290°F (1199 to 1254°C). The corresponding temperatures for a range of bituminous and sub-bituminous coals is 2150 to 2270°F (1177 to 1243°C). The fouling indexes for RDF range from 0.6 to 3.6, depending on the degree of processing, geography, and waste type, while the coals range from 0.1 to 0.9. In general, a fouling index of 1.0 or greater indicates a potential for severe tube fouling.[13] The post-test inspection of the Milwaukee County furnace indicated increased clinker formation along the grate line and more slagging in the higher areas of the furnace with RDF co-firing. However, this was not reported to be a major problem.[12]

3.1 Impact of RDF Co-Firing on Specific Boiler Types

3.1.1 Spreader Stoker

The quantity of air supplied to a spreader stoker must be adjusted to account for RDF characteristics. Due to its relatively large particle sizes and high moisture content, RDF burns more slowly than coal. Thus, much of the RDF will burn on the grate. The ratio of underfire to overfire air may have to be adjusted to account for the RDF burning pattern. If sufficient air is not supplied to the grate, fuel rich pockets will be created where trace organics can form.

3.1.2 Pulverized Coal

The temperature and velocity profiles in a typical pulverized coal fired boiler are shown in Figures 3-2 and 3-3.[18] A high temperature primary combustion zone is created in the region where the coal burns, with the peak temperature just above the top coal burner. RDF is typically injected at or above the top of this high temperature zone. Some small particles present in the RDF may be entrained and carried out of the boiler without ever having passed through the combustion zone. These particles represent a potential pathway for organic material to escape the furnace. The mass flow rate in the lower furnace is much lower than that in the upper furnace. Less material will be entrained if the RDF is injected lower in the furnace.

3.1.3 Cyclone

RDF may reduce the temperature of the cyclone due to the high ash content and low heat content. This impact is important in a cyclone boiler because the temperature must be high enough to form a slag capable of coating the lower walls of the cyclone and capable of flowing through the slag tap. The properties of RDF limit the amount that can be co-fired in a cyclone boiler.

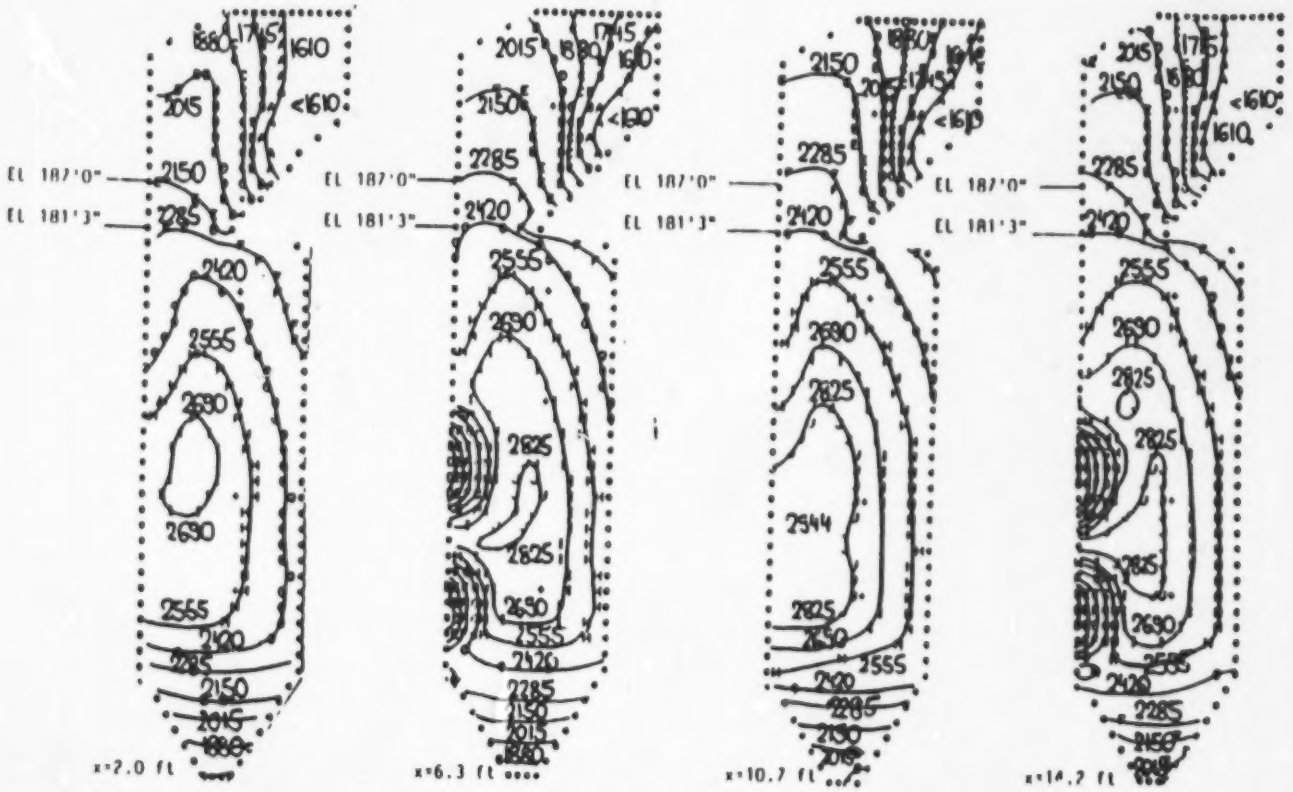

Figure 3-2. Temperature Profile in a Pulverized Coal Fired Boiler

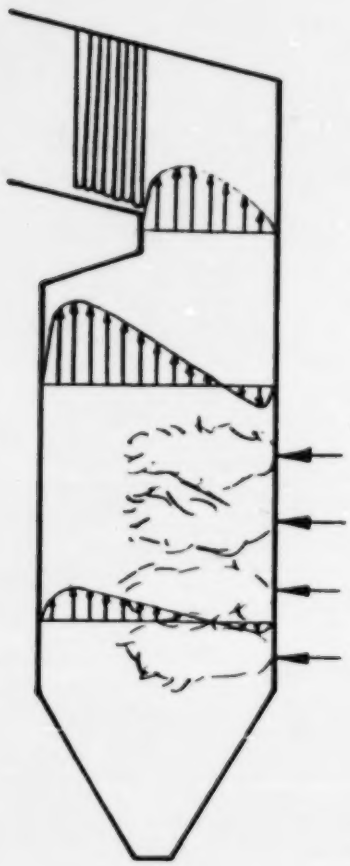

Figure 3-3. Velocity Distribution in a Pulverized Coal Fired Boiler

4.0 MODEL PLANT CHARACTERISTICS

Since RDF is currently co-fired in two fundamentally different boiler types, two model plants are recommended--one for pulverized coal wall fired boilers and one for cyclone fired boilers. These model plants are based on existing RDF co-firing utility boilers. There are no known plans to modify existing utility boilers to co-fire RDF. Should this change, it is expected that the RDF co-firing modifications and operation would not vary significantly from the existing RDF co-firing population. Therefore, these model plants are largely representative of the majority of existing utility boilers that currently or may in the future co-fire RDF. There are no known future plans to construct new utility boilers with the capability to co-fire RDF incorporated into the original design. Should this occur, these facilities may not be represented by these models.

4.1 Pulverized Coal Wall Fired Boiler Model

Two methods of firing pulverized coal are currently practiced: tangential firing and wall firing. The majority of the co-fired units in the current population use the wall firing technique so this method was selected for the model plant. The key characteristics of the model plant for pulverized coal wall fired boilers which co-fire RDF are summarized in Table 4-1. A wide variety of unit sizes are observed in the current population of co-fired units. However, increased capacity is obtained by increasing the boiler dimensions and number of burners. There is little fundamental difference between the operation of a 35 MWe unit and a 364 MWe unit. The total capacity of the 5 pulverized coal units co-firing RDF is 564 MWe, and the average unit capacity is 112.8 MWe. Based on this value, 110 MWe was selected for the model plant capacity. The number and size of the coal burners used in the boiler vary as a function of the type of coal to be burned, the physical dimensions of the boiler, and the boiler capacity. Based on current practice, the model plant is assumed to have four 100 MMBtu/hr (1.05×10^{11} J/hr) burners on each of three elevations on the front wall of the boiler.

One of the key operating parameters associated with co-firing RDF is the quantity of combustion air used. Flue gas oxygen concentrations reportedly vary from 3 to 8.2 percent (20 to 50 percent excess air) with the majority of the facilities operating near 8.2 percent O_2 (50 percent excess air). Thus, the model plant is assumed to use 50 percent excess air.

TABLE 4-1. KEY CHARACTERISTICS OF MODEL OF PULVERIZED COAL WALL FIRED BOILERS CO-FIRING RDF

FEATURE	RECOMMENDATION
Firing Method	Wall fired
Unit Size	110 MWe
Coal Burners	Four burners on each of three elevations; 100 MMBtu/burner (1.05×10^{11} J/burner)
Combustion Air	50 percent excess air
Drop Grates	Yes
Air Pollution Control	Cold side, two-field ESP
RDF Fired	10 percent of fuel by weight (95 tpd [86 tonnes/day]) (6 percent heat input)
RDF Injector Location	Two ducts above top coal burner elevation
RDF Characteristics	
Designation	RDF-3 (f-RDF)
Nominal Size	1.5 inches (0.04 m)
Ash Content	7.5 percent
Heat Content	6000 Btu/lb (1.4×10^{7} J/kg)

All of the pulverized coal fired units have been equipped with drop grates. The model plant will thus be equipped with drop grates.

All of the boilers currently co-firing RDF are equipped with cold side ESPs. Only one of the units is also equipped with a wet scrubber. The ESPs vary in size from two-field to eight-field. Two-field ESPs are more typical of current practice. Thus, the model boiler is equipped with a two-field, cold side ESP and no scrubber.

The RDF used in the current population is usually processed off-site and transported to the boiler. All the RDF used can be classified as RDF-3 (f-RDF) under the ASTM classification scheme in Table 1-1. The nominal particle sizes range from 0.75 to 2 inches (0.02-0.05 m) but the majority of the plants use RDF with a nominal size of 1.5 to 2 inches (0.04-0.05 m). The ash content of the RDF varies from 9 to 14 percent and the heat content from 4500 to 8400 Btu/lb (1.0×10^7 to 1.9×10^7 J/kg). Previous RDF combustion model studies have used RDF with an ash content of 7.5 percent and a heat content of 6000 Btu/lb (1.4×10^7 J/kg) as received. To be consistent with these previous studies, the RDF used in the model co-firing plant will have an ash content of 7.5 percent and a heating value of 6000 Btu/lb (1.4×10^7 J/kg). In addition, the RDF will be RDF-3 (f-RDF) processed off-site and will have a nominal particle size of 1.5 inches (0.04 m).

The fraction of the feed made up of RDF appears to be a function of the unit size. The smaller units typically fire 15 percent RDF while the large unit at the McIntosh plant fires only 1 percent RDF. Based on this trend, a 110 MW_e unit would fire around 10 percent RDF by weight (6 percent total heat input). All the RDF injectors are air transport type. The majority of the existing boilers contain two injectors located even with or slightly above the upper coal burner. Thus, two air transport injectors located just above the upper coal burners on the front wall of the boiler will be used in the model plant.

4.2 Cyclone Fired Boiler Model

There are two cyclone fired boilers in the current population of plants co-firing RDF, Baltimore Gas and Electric's C.P. Crane Units 1 and 2. Thus, the model plant for cyclone fired boilers will be primarily based on what is

known about the C.P. Crane units. The key characteristics of the model are listed in Table 4-2.

The C.P. Crane units each have a capacity of 200 MWe. The exact amount of combustion air used in the Crane units is not known. However, cyclone units in general operate at around 15 percent excess air. Thus, the model will be a 200 MWe unit operating with 15 percent excess air. The Crane units are equipped with only a cold side ESP. A cold side, two-field ESP will be used in the model plant.

RDF is known to make up 5 to 10 percent of the fuel used in the cyclone fired furnace. Thus, the model unit will fire 7 percent RDF by weight (4 percent of total heat input). The RDF will have the same characteristics as the RDF used in the pulverized coal model plant.

4.3 Baseline Emissions

Table 4-3 summarizes the data available from operating boilers co-firing RDF.[4,19,20] Uncontrolled particulates are generally between 3.0 and 7.0 gr/dscf at 7 percent O_2. Maximum NO_x and SO_x emissions are around 300 and 334 ppmv, respectively. The NO_x emissions from the cyclone boilers are likely to be significantly higher due to the higher combustion temperatures. While NO_x emissions do not play a role in the current analysis of co-fired units, they are important for other studies.

The only dioxin data available on co-fired units was obtained in 1983 during a detailed study of Unit 7 at the Ames facility co-firing about 20 percent RDF by weight.[4] The measurements were made by Midwest Research Institute using a Modified Method 5 sampling train. Samples were analyzed for tri- through octa-chlorodibenzo-p-dioxins and furans. No dioxins or furans were detected in the emissions. The detection limit for CDD and CDF in the composite flue gas extracts was 0.1 to 0.25 ng/dscm. The testing program at Ames was part of a larger program involving sampling of CDD/CDF from more than one facility. Substantial quantities of CDD/CDF were detected from the other plant (a mass burn MWC) using the same sampling and analytical procedures. Therefore, the emissions reported for Ames are assumed to be accurate. In addition, emissions tests have been performed at seven other coal fired boilers. No CDD or CDF emissions were detected from any of these facilities.

TABLE 4-2. KEY CHARACTERISTICS OF MODEL FOR CYCLONE FIRED BOILERS CO-FIRING RDF

FEATURE	RECOMMENDATION
Unit Size	200 MWe
Combustion Air	15 percent excess air
Air Pollution Control	Cold side, two-field ESP
RDF Fired	7 percent of fuel by weight (4 percent total heat input) (165 tpd) (150 tonnes/day)
RDF Injector Location	In cyclone burner
RDF Characteristics	
Designation	RDF-3 (f-RDF)
Nominal Size	1.5 inches (0.04 m)
Ash Content	7.5 percent
Heat Content	6000 Btu/lb (1.4×10^7 J/kg)

TABLE 4-3. EMISSIONS FROM BOILERS CO-FIRING RDF

FACILITY	UNIT	PARTICULATES gr/dscf*	NOx ppmv	SOx ppmv	DIOXINS ng/dscm
Blount	8 & 9	-	-	-	-
Ames	7	7.85‡	-	184	<0.25
	8	3.000	<299	184	-
Crane	1 & 2	-	-	-	-
McIntosh	3	5.00‡	270.9	334	-

*At 7 percent O2

‡Estimated using design ESP efficiency

These results are presented in the National Dioxin Study Tier IV Project Summary Report.[17] Thus worst case baseline emissions recommended are:

Uncontrolled particulates	7.0 gr/dscf
SOx	334 ppmv
CDD/CDF	0.25 ng/dscm

5.0 GOOD COMBUSTION PRACTICE RECOMMENDATIONS

This analysis has identified components of system design, validation, operation and control which make up good combustion practices, and that are expected to be important in the control of CDD and CDF emissions from facilities which co-fire RDF. In addition, preliminary recommendations have been made for values of the individual components. Identification of the elements and formulation of the recommendations are based upon current design practices and combustion experience. The combustion control elements and preliminary recommendations are summarized in Table 5-1.

RDF co-firing is defined as the combustion of RDF along with another fuel in a device designed primarily to burn the other fuel. The existing facilities which comprise this population of MWCs all co-fire RDF in coal fired boilers. The design of coal fired boilers is complex undertaking, well beyond the scope of this report. It is assumed that the design and operation of coal fired boilers meet the criteria for good combustion. The primary focus of this study is on design and operating features which directly relate to the co-firing of RDF.

5.1 Design

Several elements must be considered in the design of RDF co-fired facilities. These elements include:

- Combustion temperature
- Combustion air
- Quantity of RDF co-fired
- Downstream temperatures

Whenever possible key parameters which can be used to assess a given design are identified. However, it is not always appropriate to identify a single parameter and assign it an acceptable value for each of the elements. In those cases where a single parameter cannot be identified, the key design considerations are discussed.

TABLE 5-1. GOOD COMBUSTION PRACTICE RECOMMENDATIONS FOR COMMERCIAL/UTILITY BOILERS CO-FIRING RDF

ELEMENT	COMPONENT	RECOMMENDATION
Design	Downstream temperatures	Cold side ESP with entrance temperature <450°F (232°C)
System Validation	Oxygen in flue gas	3-9 percent dry basis
	CO in flue gas	150 ppmv at 7 percent O2 on four hour average
	Exit gas temperature	Gas entering the ESP <450°F (232°C)
Operation/Control	Oxygen in flue gas	3-9 percent dry basis
	CO in flue gas	150 ppmv at 7 percent O2 on four hour average
	Start-up procedures	Attain steady temperature firing coal before introduction of RDF
	Exit gas temperatures	<450°F (232°C) entering ESP

5.1.1 Temperature

The temperature distribution in a typical wall fired coal combustor is shown in Figure 3-2. The temperatures in coal fired boilers are significantly higher than those in a typical waste combustor. The peak temperature shown is over 2900°F (1593°C). The maximum variation in temperature from the wall to the centerline is 390°F (199°C). This can be compared to the typical temperature distribution in a mass burn combustor shown in Figure 5-1.[19] The peak temperature in the mass burn unit is only 1832°F (1000°C) and the variation from the centerline to the wall is over 360°F (200°C).

The minimum temperature pathway open to combustion gases must be sufficient to destroy CDDs, CDFs and their precursors. Thermal decomposition data obtained by UDRI can be used as the basis for indicating the temperature which will be required to destroy organics. Some of the reference data for a range of organic intermediates including CDDs, CDFs, benzene and chlorinated hydrocarbons is shown in Figure 5-2.[21] CDD and CDF species are generally unstable above 1300°F (704°C) although potential precursors like chlorophenols are stable to 1500°F (815°C). Hexachlorobenzene is one of the most stable species. It does not totally decompose below 1650°F (899°C).

The furnace exit gas temperature (FEGT) is frequently used to characterize coal fired boilers. This temperature is the mass average of the gas temperatures measured at the entrance to the convective heat recovery section of the boiler. The FEGT is typically around 2000°F (1093°C) under normal operating conditions. Thus, even at the exit to the furnace the minimum temperature would be well above 1650°F (899°C). It is unnecessary to specify a minimum FEGT since the temperatures required for normal operation of a boiler are well above the minimum temperature requirements.

5.1.2 Combustion Air

An excess of combustion air is essential for the complete oxidation of combustible material. Combustion will not be completed and harmful intermediate species may form and escape the furnace if oxygen is not provided in sufficient quantities at the appropriate locations. Coal fired boilers are currently designed to provide the appropriate amounts of air for efficient combustion of coal.

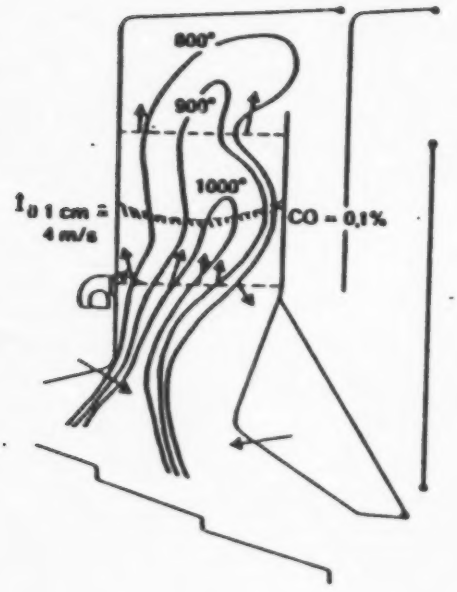

Figure 5-1. Temperature Distribution in a Typical Mass Burn Waste Incinerator

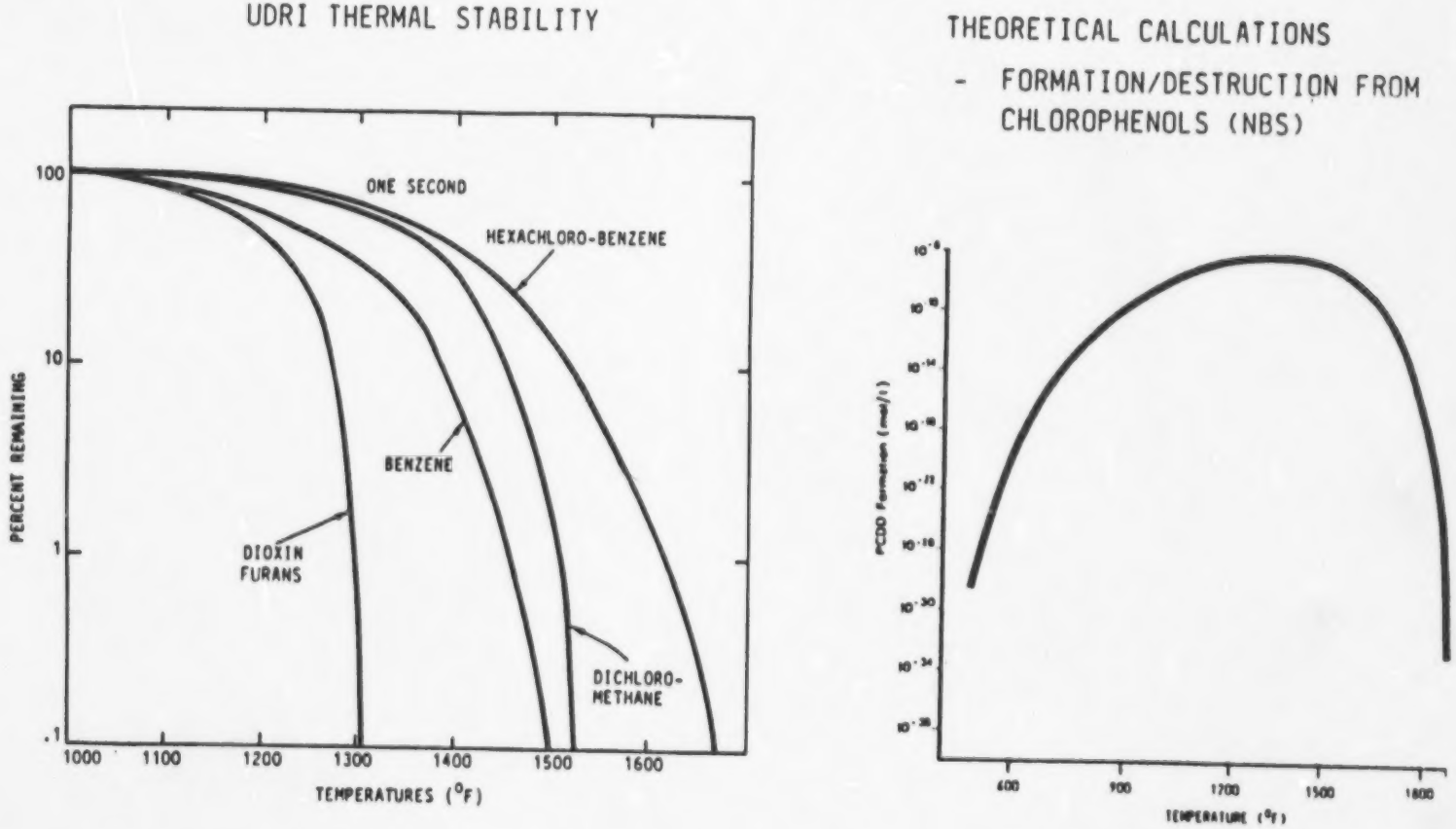

Figure 5-2. Thermal Decomposition Characteristics of Selected Hydrocarbons

Combustors which fire RDF must account for the variability of the waste. Boilers which fire a fuel made up entirely or in large part by RDF must use relatively large amounts of excess air to account for time and composition variations in the waste. Boilers which fire only RDF use as much as 100 percent excess air. Boilers which use fuels that contain relatively small amounts of RDF do not require as much excess air. Typical coal fired boilers use as little as 15 percent excess air. Thus, the quantity of excess air required to insure good combustion is a function of the fraction of RDF in the fuel. Particulate carryover can be affected by the location and distribution of combustion air and therefore should be considered in the design of RDF co-firing systems.

Because of its high moisture content and large particle size, RDF requires more time to burn out than coal. This results in bottom ash with a relatively high carbon content in pulverized coal fired boilers. Drop grates are installed to catch the ash before it enters the ash hopper, extending the time it is exposed to the high temperature environment. Undergrate air must be supplied to ensure complete oxidation of the combustible material on the grate.

5.1.3 RDF Feed

The compositions of typical RDF and a typical bituminous coal were shown in Table 3-2. RDF contains more moisture, inert material and typically has half the heat content of coal. RDF burns more slowly and at a lower temperature than coal. Current practice indicates that when RDF makes up more than 20 to 30 percent by weight of the fuel (10 to 15 percent of total heat) it becomes difficult to maintain consistent temperatures. Extensive modifications to the ash handling system, air injection system, flue gas handling system, and combustion chamber may be needed to effectively burn a fuel that contains more than 30 percent RDF.

Table 3-2 also shows that RDF contains significantly more chlorine than coal. Chlorine in the feed forms HCl. HCl in the flue gases can cause extensive corrosion problems in the cooler sections of the boiler and downstream ductwork. Thus, care must be taken when large quantities of RDF are co-fired.

Uniformity in the density and feed rate of the RDF will help to ensure the stability of a co-fired system.

5.1.4 Downstream Temperature

Current theory suggests that toxic organic pollutants like CDDs and CDFs can form downstream of the combustion chamber. Even with a FEGT as high as 2000°F (1093°C), trace amounts of CDD and CDF precursors can escape the furnace and travel downstream due to imperfect mixing within the furnace. Laboratory and field data indicate that these reactions involve fly ash particles and occur at temperatures between 480°F and 660°F (249°C and 349°C). The reactions are relatively slow, requiring from 15 minutes to several hours to produce measurable quantities of CDD and CDF. Thus, to minimize the formation of CDD and CDF downstream from the combustion chamber, the residence time at temperatures between 480°F and 660°F (249°C and 349°C) must be minimized (i.e., the quench rate through these temperatures should be maximized).

Fly ash is retained at a number of locations in a boiler including tube surfaces, the air heater, and the ESP. The ESP retains the largest number of particles, is the most likely piece of equipment to be in the critical temperature window, and typically has a long particle residence time. In addition, the ESP is usually the last location in a boiler where particles are collected. Thus, to minimize CDD/CDF emissions, the temperature at which the ESP is operated should either be greater than 660°F (349°C) or less than 480°F (249°C). In practice, this will generally mean the use of a cold side ESP with an entrance temperature of 450°F (232°C) or less.

5.1.5 Good Combustion Practice Recommendations

While it is important that the furnace temperatures remain above 1800°F (982°C), the temperatures required for normal boiler operation are well above this value. Thus, no minimum temperature is needed in the guidance. It is necessary to increase the quantity of combustion air provided to account for RDF variability. The exact amount of air required is a function of the fraction of RDF in the feed. The quantity of RDF fed is a key design criterion. However, a number of factors including ash handling capacity, flue gas capacity, and ESP capacity may be important. Thus, the RDF feeding limit must be evaluated on a case by case basis. Downstream temperatures are more

straightforward. Particles should not experience a long residence time at temperatures between 450 and 660°F (232°C and 349°C).

5.2 System Validation

5.2.1 Flue Gas Oxygen Content

The flue gas oxygen content is directly related to the total amount of combustion air supplied. Problems are experienced when either too much or too little air is provided. Too much excess air can excessively cool the furnace and quench hydrocarbon oxidation reactions. Too little air leaves oxygen-starved conditions either throughout the furnace or in localized zones. The total air flow must be sufficient to:

- ensure that there are no oxygen deficient local zones caused by inadequate mixing;
- dampen out surges due to excessively volatile refuse.

In other words, there must be sufficient excess oxygen available to dampen out spatial and temporal variations in oxygen concentration. The range of excess air that is appropriate can be established based on current practice. Coal fired boilers operate best with flue gas oxygen levels between 3 and 9 percent. Since RDF makes up only a small fraction of the fuel this range has also been found appropriate for co-fired systems.

5.2.2 CO in Flue Gas

Low mean CO levels are indicative of good overall combustion but cannot account for isolated low temperature or oxygen deficient pathways which could lead to trace organic emissions. Therefore, low CO levels do not necessarily assure that complete mixing occurs in the furnace, which is crucially important to ensuring destruction of intermediates. However, once a system has been proven to have well-mixed conditions by in-furnace CO profiling or other means, then flue gas CO levels provide a useful indication that no significant change has taken place. There are extremely limited CO emissions data available from RDF co-fired boilers. However, as shown in Figure 3-1, data gathered at the St. Louis Meramec Plant demonstrate that co-firing RDF at less than 30 percent by weight does not significantly change CO emissions relative to those achieved during 100 percent coal firing. Based on this

data, it can be assumed that co-fired facilities can achieve CO levels that are typically measured from coal fired boilers. Wall-fired, tangentially-fired, and cyclone-fired boilers are expected to be able to achieve CO emissions of 150 ppmv (four hour average, corrected to 7 percent O_2). Therefore, this value is selected as a baseline for the model plants.

5.2.3 Exit Gas Temperature

As was mentioned above, the temperature of the ESP can play an important role in determining the downstream formation of CDD/CDF. It is important that the ESP be operated outside the temperature window where CDD and CDF formation has been observed. For a cold side ESP, this means that the temperature of the gas entering the ESP should be below 450°F (232°C).

5.3 Operation and Control

Once a system is designed, built, and tested, it must be continually operated according to design and monitored to ensure that the combustion conditions do not deteriorate. Parameters to be monitored include:

- Flue gas oxygen concentration
- Flue gas carbon monoxide concentration
- Gas temperature entering ESP

These variables will ensure that the system remains within the proper operating envelope.

The procedures used to start up and shut down a boiler co-firing RDF are important. The recommended procedures are largely based on current practice and experience. Before RDF co-firing begins, the boiler temperatures should be stabilized using only coal. This ensures that no low temperature pathways exist. During shut-down RDF co-firing should be discontinued first. Once again, this ensures that no low temperature pathways through the furnace exist while RDF is being fired.

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